Is a Production Level Scanning Electron Microscope Linewidth Standard Possible?

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ABSTRACT

Metrology will remain a principal enabler for the development and manufacture of future generations of semiconductor devices. With the potential of 130 nm and 100 nm linewidths and high aspect ratio structures, the scanning electron microscope (SEM) remains an important metrology tool. This instrument is also extensively used in many phases of semiconductor manufacturing throughout the world. A challenge was recently posed in an article in *Semiconductor International*. That challenge was to have an accurate, production level, linewidth standard for critical dimension scanning electron microscopes available to the semiconductor industry. The potential for meeting this challenge is explored in this paper.

Key Words: Scanning Electron Microscope, Standard Reference Material, SRM, Atomic Force Microscope, AFM, polysilicon, critical dimension, linewidth, metrology

1.0 INTRODUCTION

Metrology will remain a principal enabler for the development and manufacture of future generations of semiconductor devices. With the potential of 130 nm and 100 nm linewidths and high aspect ratio structures (e.g., 5:1 or 7:1), the scanning electron microscope (SEM) remains an important tool that is extensively used in many phases of semiconductor manufacturing throughout the world. The SEM still provides higher resolution analysis and inspection than that afforded by current techniques using the optical microscope and higher throughputs than scanned probe techniques. Accurate metrology with this instrument requires the development and availability of traceable standards. Today, magnification (line scale) calibration artifacts traceable to the *Le Système International d'Unités* (SI) units are available for the SEM, but a traceable width standard is not. Traceability

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to the meter is typically achieved through measurement with laser interferometry (See: Section 1.2.2).

In this paper we will explore why the development of a relevant linewidth Standard Reference Material (SRM) for the scanning electron microscope, optical microscope or scanned probe instrument is not a simple task. The reason there has not been a SEM linewidth standard available is that significant technical barriers have existed which have kept a useful production relevant critical dimension standard from being issued either for SEM, optical or scanned probe microscopes. However, through recent collaborative research funded in part by International SEMATECH (ISEMATECH) and the Office of Microelectronics Programs at NIST, some of these barriers have been overcome. Today, semiconductor production has progressed to a point where accurate production relevant critical width standards are definitely needed. A challenge was posed in an editorial article by Alexander Braun in *Semiconductor International* (Braun, 1999). This challenge was to produce an accurate, production level critical, linewidth standard for critical dimension scanning electron microscopes (CD-SEM). Research has progressed to the point where such standards can become available with an acceptable level of measurement uncertainty. The potential for meeting this challenge is explored in this paper.

1.1 Overcoming the Barriers

During the past several years, four significant technical areas directly related to the development of production relevant, linewidth standards have dramatically improved. The first area is modeling. Collaborative work between NIST, ISEMATECH, and other researchers has led to vast improvements in the understanding of the electron beam interaction and the modeling of that process (discussed below). ISEMATECH support in the modeling area has been crucial to the progress that has been made. The ISEMATECH co-sponsoring with NIST of several Electron Beam/Instrument Interaction Workshops at the SCANNING International meetings over the past several years has provided a forum that, for the first time, drew SEM modeling experts from all over the world. This has resulted in significant and rapid progress in the area of electron-beam interaction modeling. Through the work of Dr. Jeremiah Lowney, the NIST MONSEL series of computer codes have been significantly improved (Lowney, 1996) and experimental verification of the modeling has been excellent on defined structures (Lowney et al., 1995). These codes have been made available to researchers worldwide.

Second, confidence in the model has been fostered by extensive comparisons to other experimental computer codes (Lowney et al., 1995) and to a commercial computer code through a NIST/Spectel Company model comparison partially funded by ISEMATECH. This forward-looking project also facilitated the third component - a partially ISEMATECH funded linewidth correlation project (Villarrubia et al., 1999). The linewidth correlation study, for the first time, carefully applied three different metrology methods to a defined structure. More importantly, an uncertainty of each of the measurement processes was rigorously assessed and reported. This remains an ongoing project with a new sample and it ties directly to the development of an SEM linewidth standard This work strongly fostered NIST's confidence in the ability to develop a relevant width standard.

The ability to fabricate a resilient linewidth sample is the fourth component. This barrier has also been overcome through the ISEMATECH Advanced Metrology Advisory Group interactions and support. It is believed that a resilient, high-quality production relevant artifact can be fabricated. This will be discussed in a later section (See; Section 2.0).

1.1.1. Linewidth Issues. The issue associated with the measurement of the width of a structure is that inferring that width from its image or linescan requires assumptions about how the instrument interacts with the sample to produce the image, and how, quantitatively, the resulting apparent edge positions differ from the true ones. Figure 1 demonstrates this for an optical photomask.

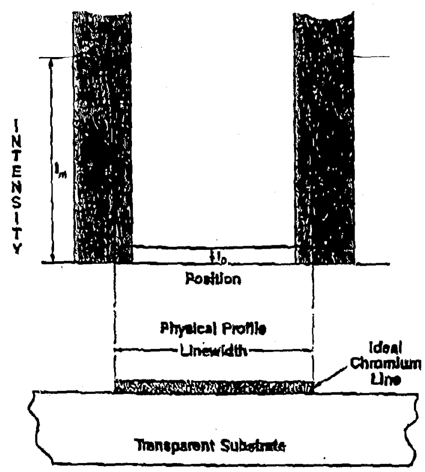

Figure 1. Comparison of the intensity profile, which is a convolution of the instrument response and the signal derived from a photomask sample. Note that the area shown in gray indicates the area where the actual edge can lie. The position of the edge on the waveform can only be determined through modeling (drawing courtesy of James Potzick).

In Figure 1, the line profile is intentionally compared directly to the actual structure. That profile is a convolution of the signal from the sample and the response of the instrument itself. The gray area denotes the region of the profile from which the edge can be measured. Due to the sample and instrument specific contributions, the actual physical edge can lie anywhere within that region. Measurement algorithms are then applied to this waveform to calculate the measurement. Current algorithms do not consider these contributions, but if the algorithms are robust, they can provide a high degree of repeatability. Assigning edge locations with a useful uncertainty to points inside the gray regions in order to obtain an accurate measurement can only be done based on a model. Clearly, in the extreme case, if one is willing to accept an uncertainty as large as the gray box, a model would be unnecessary and any algorithm would suffice. Furthermore, without the modeling coupled to the measurement, there is no justification for a claim of accuracy in the measurement process. To underscore this point, and the fact that different algorithms use various measurement criteria to determine a measurement result, Table 1 shows the results of the application of several commercially available algorithms to the measurement of a simulated line image (Postek et al., 1998). A simulated image is extremely valuable in this measurement because all the input parameters to the simulated image are known hence the pitch, linewidth and space width are known.

Table 1 - Comparison of SEM Measurement Algorithms

Algorithm	*Space Width (nm)*	*Linewidth (nm)*
Peak	109.52	91.15
Threshold	91.65	110.6
Regression	75.63	125.9
Sigmoid fit	92.95	110.52

The discrepancy between different measurements and different algorithms is not surprising. A similar discrepancy among width measurements was demonstrated in a SEM Interlaboratory Study (Postek et al., 1993). To accurately determine where the measurement of width should be made on the intensity profile, a model is required.

1.1.2 Unraveling the Onion. For the initial steps in understanding the "probe-sample" interaction in the SEM quantitatively, and to verify models of instrument behavior, the linewidth correlation work employed highly idealized samples, fabricated in single crystal silicon (Villarrubia et al., 1999). Lines were electrically isolated from the underlying wafer by a 200 nm thick silicon oxide to permit electrical critical dimension (ECD) measurements. Clearly, the potential of sample charging can compromise this measurement in the SEM and care to minimize this risk was taken in the NIST measurements. Although this is not a production relevant sample *per se*, it did prove to be a useful tool in this correlation experiment (Table 2). Experiments such as these provide needed data regarding instrument response and modeling. However, the probe-sample interaction is notoriously a function of the sample as well as the instrument. This also raises a question: to what extent will corner rounding, deviations from ideally vertical sidewalls, or surface and edge roughness (all imperfections likely to be encountered in actual production samples) affect linewidth measurement accuracy? Research on these topics is currently being continued under a new ISEMATECH contract. It is important to test our understanding for samples that approximate as closely as possible the product samples of greatest industrial interest. Today these types of samples can be made and a confidence has developed that a traceable linewidth sample can be issued. Continued research in this area is required for success in developing such a production relevant standard reference material and a model that can handle a wider variety of input parameters and typical manufactured products.

Table 2 - Linewidth Results on Single-Crystal Silicon Sample

Technique	*Width (nm)*	*3σ Uncertainty (nm)*
SEM	447	7
AFM	449	16
ECD	438	53

1.1.2.1 Specimen Charging. Specimen charging also remains a problematical area for SEM metrology affecting both accuracy and reproducibility. Dealing only with fully conductive samples is one approach to the problem, but in the real world of semiconductor production, many of the materials of interest are not conductive. Modeling of specimen charging is currently in progress at NIST and elsewhere (Ko and Chung, 1998,1999; Ko et al., 1998; Grella et al. 1994) but with the capricious nature of the charging and the specimen and instrument dependencies, this presents a very difficult and extremely interesting research problem. Continued work in this area is also needed.

1.2 CD-SEM Reproducibility or Accuracy

Semiconductor production is strongly dependent on the precision of the chip manufacture. The closer the product is manufactured to the desired specifications, including the size of individual integrated circuit parts, the better the yield, and hence the higher the profitability. The accuracy of device dimensions and their relationship to design, models and tolerances is another question altogether. Depending on the philosophy and needs of a semiconductor company, the importance of accuracy will vary between the process development phase, pilot line, or production line. In any event, to achieve an accurate measurement, standards traceable to the SI units are necessary.

1.2.1 Accuracy. Accuracy of a measurement is defined as:

> "Closeness of the agreement between the result of a measurement and a true value of the measurand" *(International Organization for Standardization, 1993).*

(reviewed by Nyyssonen and Larrabee, 1987). This work was comprised of three major components to arrive at the necessary traceability. The first component was the development of a certification instrument that could be modeled and fully characterized. The second was the development of a suitable artifact that could be modeled and the third and major component was the metrology model itself. This resulted in the issuance of the photomask standard, SRM 473, the first traceable photomask standard. This standard resulted in major changes in the way that the industry viewed metrology as well as documented savings to the industry (Charles River Associates, 1981).

Limitations in optical metrology led to the application of scanning electron microscope-based metrology to critical dimension (CD) metrology. This field has blossomed and significant instrument improvements have been made (Postek, 1994; Postek, 1997). Many more improvements will likely ensue. Efforts have been underway to develop an SEM linewidth standard for some time. A similar triumvirate of sample, instrument, and model is required. As stated earlier, in some instances, the progress that has ensued has already resulted in the application of the technology to potential accurate standards development for x-ray mask metrology (Postek et al., 1993 a and b) and SCALPEL masks (Farrow et al., 1997; Liddle et al., 1997).

1.2.2 Traceability. Traceability is a desired feature for any linewidth standard. The definition of traceability is:

> *"The property of a result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties (International Organization for Standardization, 1993). "*

Traceability is a way of approaching the concept of "accuracy" in actual practice. A measurement could, in principle be very reproducible but also very inaccurate. Reproducibility is a necessary but not sufficient condition for accuracy. What is needed in addition to reproducibility is some tie to the "true value" as defined for accuracy. Traceability to a NIST standard is one way of achieving this. For NIST, the most convenient way to achieve traceability in length measurements is via laser interferometry. Laser interferometry provides a tie to the meter. The meter is internationally defined as "the length of the path traveled by light in vacuum during a time interval of 1/299,792,458 of a second." This definition has the effect of fixing the speed of light, c, to 299,792,458 m/s. Once the frequency, f, is measured, the wavelength is readily determined. The uncertainty of frequency determination is negligible for these purposes owing to the high accuracy with which time can be measured using atomic clocks. Because the wavelength is typically measured in air while the meter is defined for the vacuum, corrections (where applicable) must be applied which account for the actual index of refraction in air. These corrections, too, are known with small uncertainty compared to the remaining steps in the traceability paths.

1.2.3. Uncertainty. Uncertainty is an additional concept that measures how close to the "accurate" value an experimental result lies. Clearly, NIST cannot make perfect standards and there is always some nonreproduciblilty error in the measurement. There is also some error in relating its calibration measurements back to the "true value." The combination of these errors is called uncertainty. In the linewidth correlation study (Villarrubia et al., 1999) an uncertainty budget was developed according to NIST guidelines (Taylor and Kuyatt, 1994), which listed the major components contributing to the measurement uncertainty. Listing these components in a careful manner provides a tool for determination of opportunities for improving the measurement process and thus its accuracy.

In order to complete the traceability chain, metrologists are required to calculate and state an uncertainty of their measurements with respect to a National Metrology Institute (NMI). The NMI is required to demonstrate traceability to the International (SI) system of units maintained by the Bureau International des Poids et Measures (BIPM, 1983). One thing that is important to remember about traceability is that it is often a legal or contractual requirement.

1.2.4. Traceability Chain. Just as a literal chain is composed of nodes joined by links, so is the traceability chain. The nodes are measurable things and the links are measurement processes that define, quantitatively and with stated uncertainty, the relationship between these things. The simplest and most straightforward of the various paths to traceability is shown in Figure 2 for pitch (displacement) measurements. In this path, the product sample is tied to the SI unit of length through a primary metrology instrument (Path 1) or a calibrated secondary standard generated on a measurement instrument (Path 2). This is the current mechanism of traceability for SRM 484, SRM 473, SRM 474 and SRM 475. This is also the planned track for the new SEM magnification standard SRM 2090 once it has been fabricated. The reader should note that in order to keep the diagram simple, any application of modeling in this figure has been intentionally avoided by focusing only on pitch measurements.

The accurate primary standard can be used to develop secondary or working standards for the production shop floor as shown in the lower section of the illustration. The potential of atom–based artifacts and new metrology approaches to the traceability of artifacts is also being pursued (Silver et al., 1998) and will be published, at a later date.

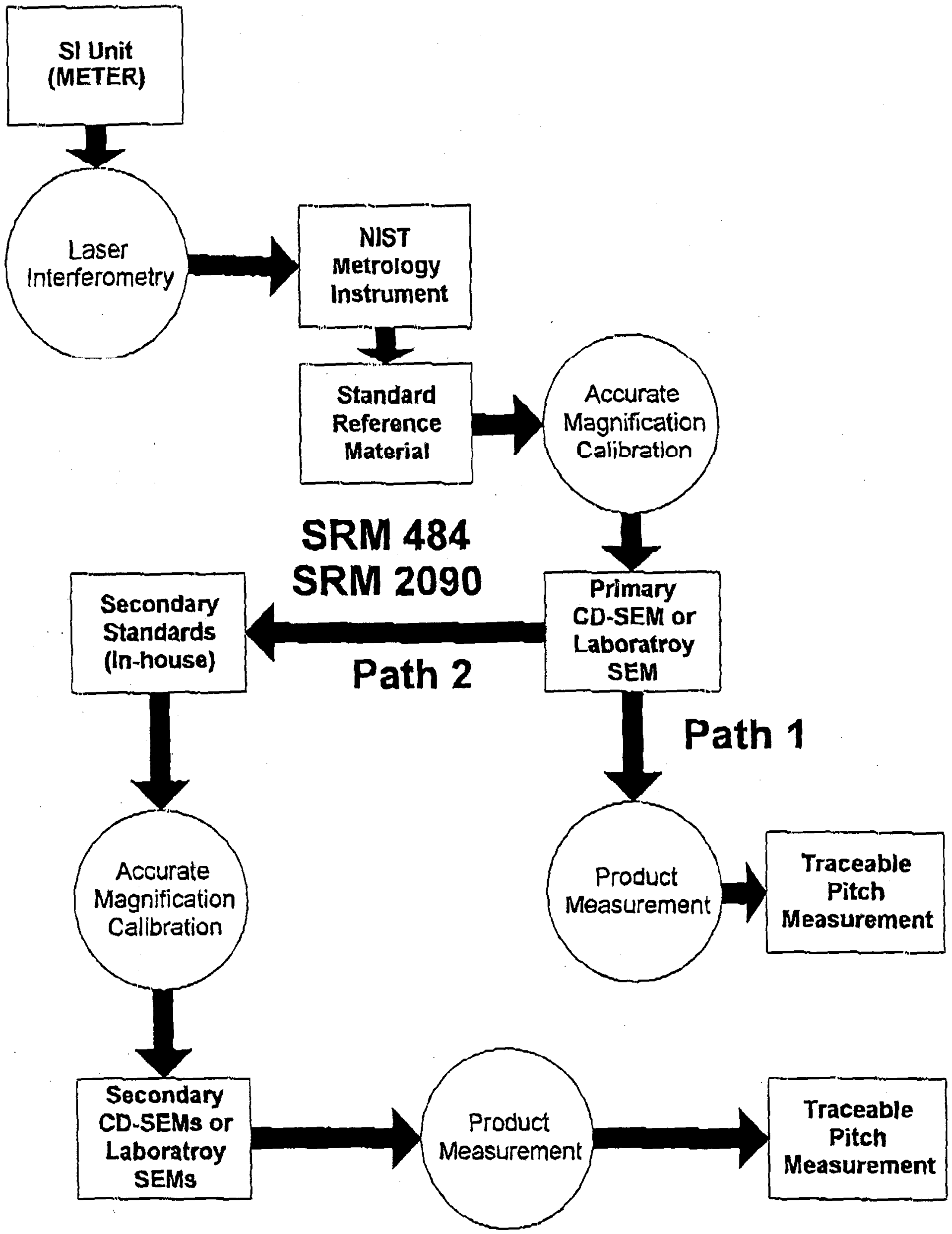

Figure 2. Diagram of a sample pitch traceability chain for primary and secondary standard calibration of an instrument. [Note: to keep the traceability diagram simple, any application of modeling in this figure has been intentionally avoided by focusing only on pitch measurements.]

2.0 PROCESS RELEVANT SEM LINEWIDTH SAMPLE

A NIST team with expertise in SEM, AFM, optics and other dimensional metrology tools in collaboration with members of the ISEMATECH Advanced Metrology Advisory Group (AMAG) has designed a linewidth prototype, test sample. This sample will be fabricated in polysilicon by ISEMATECH, thereby providing a semiconductor process-relevant metrology object. The design will incorporate isolated and dense lines with drawn linewidths ranging from 100 nm to 1 μm. It will contain pitch features measurable both by the width measuring tools and by traceable pitch-measuring instruments (e.g., the NIST Linescale Interferometer), in this way to minimize scale (magnification calibration) errors in the linewidth measurement. A prototype of the pattern, which will be incorporated into the soon-to-be, produced ISEMATECH AMAG sample is shown in Figures 3 and 4.

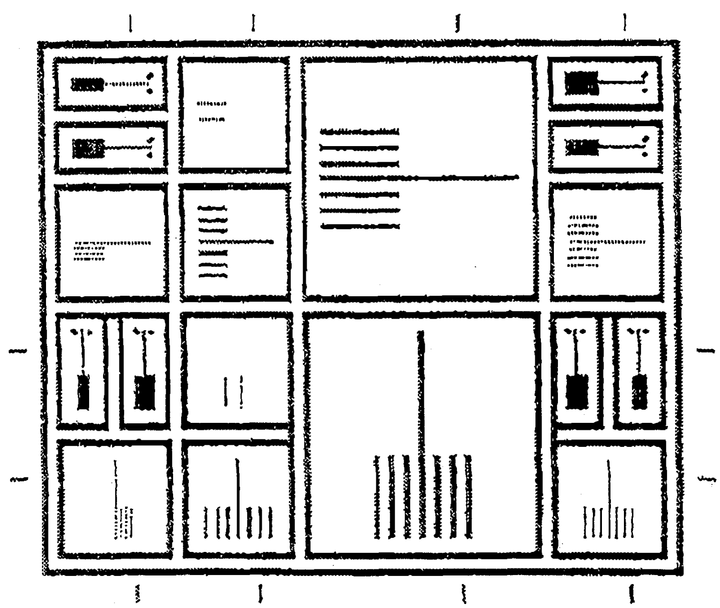

Figure 3. Illustration of the prototype linewidth pattern to be fabricated polysilicon on the soon to be produced AMAG wafer set.

Figure 3 shows a proposed linewidth test artifact. A cell, comprised of several patterns containing isolated and dense features with nominal widths ranging from 100 nm to 1.0 μm in two orientations is shown. The 1.0 μm wide spaces between patterns are designed to be visible in the NIST linescale interferometer, with their spaces traceably measurable by it, thereby providing an integral scale reference.

Figure 4 describes the detail of one of the patterns. Each pattern contains focus and astigmatism fiducial marks (the crosses) as well as isolated and dense lines.

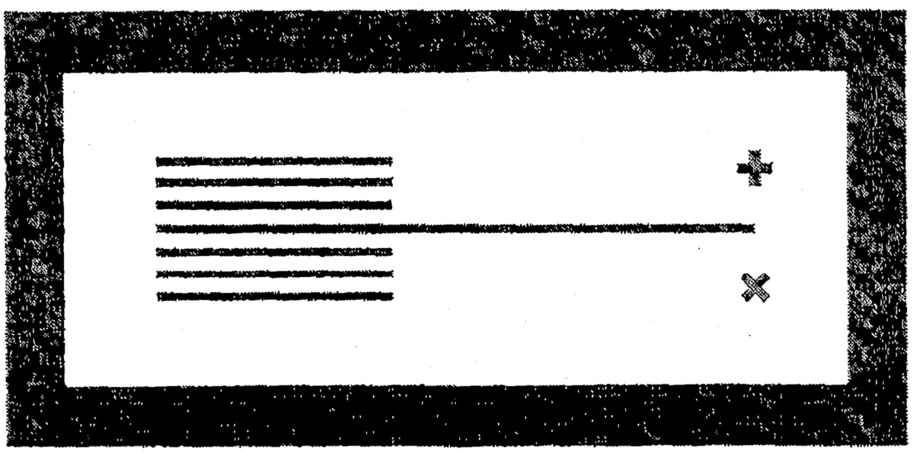

Figure 4. Illustration of one of the individual pattern cells of the prototype linewidth test pattern.

The sample will be measured by top-down SEM, optical metrology instruments, and by NIST's Calibrated AFM. A detailed uncertainty budget will be calculated for the measurements. The current metrology models will be applied and this information will then be used to refine the measurement protocols and improve measurement accuracy. Design of any sample is inevitably a compromise between competing factors. A sample that is intended to be measured by a large number of techniques may be measurable by all, but optimized for none. By focusing on AFM, SEM, and optical measurements in the current study, the capability for electrical measurements utilized in the previous linewidth correlation work (Villarrubia, 1999) is lost. However, the potential for specimen charging artifacts associated with the measurement process is significantly decreased. The main advantage of the new sample is that it will more nearly approximate industrial samples of interest (which are polysilicon without underlying thick oxide). In that way, it moves us a step closer to a certified linewidth SRM.

3.0 NIST SEM METROLOGY INSTRUMENT

The metrology triumvirate described earlier is composed of the model, sample and instrument. The semiconductor industry desires traceable standards on the wafer dimensions in current use. The polysilicon linewidth sample described above can be made with standard process technology and thus can be fabricated with current wafer fabrication technology. The NIST MONSEL model as well as the commercial model studied provides excellent results. However, the current NIST metrology SEM instrument remains the weakest link. The metrology SEM at NIST is old lanthanum hexaboride (LaB_6) technology and not the current field emission technology. This instrument is suitable for pitch calibrations but the resolution is inadequate for linewidth metrology. This instrument also has a serious sample size limitation, which is not compatible with current semiconductor production. For the scanning electron microscope, small, diced standards can be developed and placed into drop-in wafers, but the industry actually requires wafer-sized standards. This creates a certification, as well as, a fabrication problem. In order to certify wafer size standards, an instrument with SI traceability must be able to accept such large samples. NIST does not currently have such an instrument however an internal NIST initiative is currently in process to obtain the needed tool. Alternative approaches to the certification process are also being explored. Second, the economy of scale issues must be considered. Printing a single pattern or some small, multiple number of patterns on a 300 mm wafer (or larger) is not cost effective. A diced 300 mm wafer can produce about 200 SRMs versus a single SRM from an intact wafer. The economics and details of these issues have yet to be completely resolved.

4.0 CD METROLOGY VISION

The work described in this paper defines an evolutionary sequence leading to a linewidth standard for the SEM (Figure 5). Are all the necessary modeling components in place at this time? No. There is more fundamental work, which needs to be done by both research institutions and SEM manufacturers before this overall goal can be fully achieved. However, useful research materials can be made available in the interim. Tremendous progress in the electron beam modeling has occurred due to the work and support of many institutions and individuals. However, there remains a good deal to accomplish - especially where instrument response modeling is concerned. The SEM manufacturers must play an active role in the successful completion of this component.

The vision for the future revolves around a concept referred to as "model-based metrology." Model-based metrology (MBM) combines all the components needed to accurately measure a structure into one aggregate program embedded in the measurement instrument. MBM would include electron-beam interaction modeling, instrument response modeling, the charging model and any other necessary components into a single program. Then, perhaps only a single NIST traceable calibration standard would be placed initially into the instrument to calibrate the metrology program and the instrument response. If the remainder of the model components were good enough, any material could be placed into the metrology instrument and accurate measurements could be made. A good deal of research needs to be done in order to achieve that level of sophistication in the modeling. Nevertheless, it is possible.

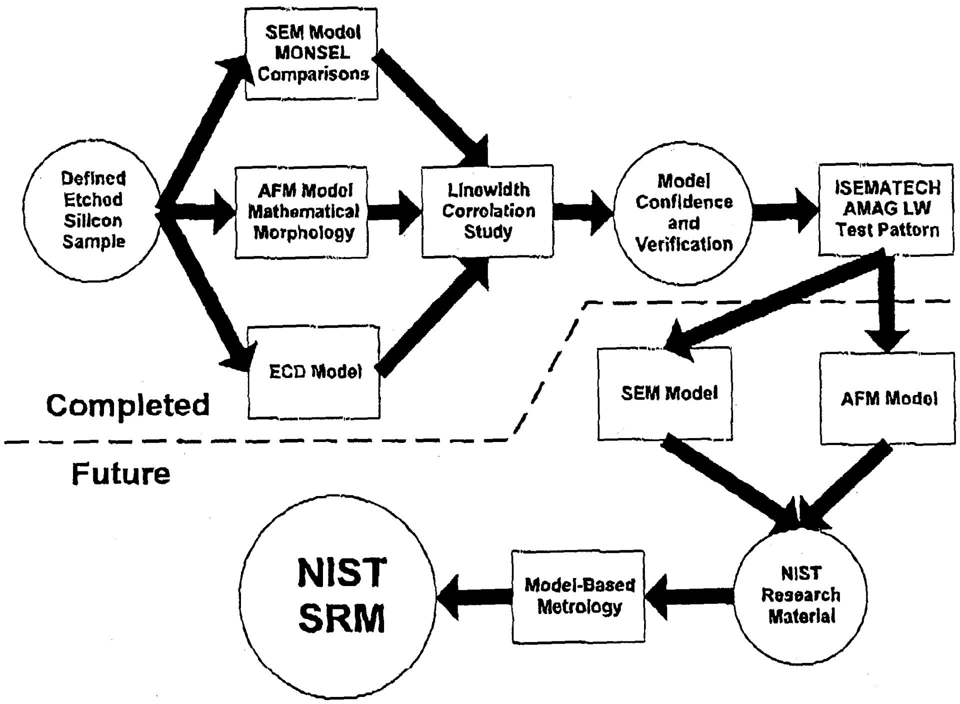

Figure 5. Evolutionary sequence as described in the text for the SEM linewidth standard.

5.0 CONCLUSIONS

A process-specific prototype linewidth standard has been designed for the scanning electron microscope and it is currently being fabricated through the collaboration with the Advanced Metrology Advisory Group of ISEMATECH. Traceability paths have also been defined for this standard and the extension to a NIST traceable SRM.

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